A Desktop Interferometer for Optical Synthesis Imaging

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ABSTRACT

A simple desktop optical interferometer is described and demonstrated as a teaching tool for concepts of long-baseline stellar interferometry. The interferometer is compact, portable, and easily aligned. It sits on a base 8″×10″ and uses an aperture mask which is mounted to rotate within a precision ball-bearing. Fringes produced from an artificial star are observed through a microscope by means of a video camera and are displayed on an overhead television monitor. When the aperture mask is rotated rapidly, the rotating fringe patterns seen on the monitor are observed to synthesize sources that are unresolved by individual holes in the mask. Fringes from an artificial double star are used to illustrate the relationship between fringe visibility and source structure and to demonstrate image synthesis.

Keywords: Interferometry, optical, synthesis imaging, teaching

1. INTRODUCTION

This paper describes a small optical interferometer that is useful for teaching concepts of aperture synthesis imaging. The overall concept for the interferometer was developed by Donald Wilson at the University of Cambridge in 1996. The Royal Society had extended an invitation to the COAST group to prepare an exhibit for the public at the Royal Society's open-house in London in 1996. The demonstration that was developed in response to this request proved useful for engaging a wide range of audiences, from the general public to under-graduate and graduate-level students, as well as professional scientists. Following the open house, the interferometer was modified and used extensively by John Baldwin for public lectures.

A more compact version of the interferometer, described in this paper, was developed at the Jet Propulsion Laboratory for the Michelson Interferometry Summer School program. The principles and operation of the interferometer are described here.

2. THEORY

The resolution of a conventional telescope is ultimately limited by its aperture diameter, D. If there are no aberrations, the smallest angular structure that can be resolved at a wavelength λ is $1.2\lambda/D$, which is the half-width of an Airy pattern—the distance from the peak of the Airy pattern to the first intensity minimum—and describes the smallest angular separation where two point sources can still be distinguished as separate. However, if two telescopes are used to produce interference fringes, the angular resolution becomes $\lambda/(2B)$, where B is the baseline separating the telescopes. As the baseline is increased, the interferometer is able to resolved objects of smaller and smaller angular size.

A very simple way of illustrating this in the lab is to look at the fringes produced by two small apertures when illuminated by a bright point source and viewed under high magnification through a microscope. The microscope magnifies the diffraction pattern, making the Airy disk and the fringes across it readily visible. It is then straightforward to show that whereas a single aperture can see detail at angular scales comparable to the Airy pattern, the combination of *two* apertures is sensitive to much smaller angular scales—comparable to the fringe width, which can be made arbitrarily small by increasing the aperture separation.

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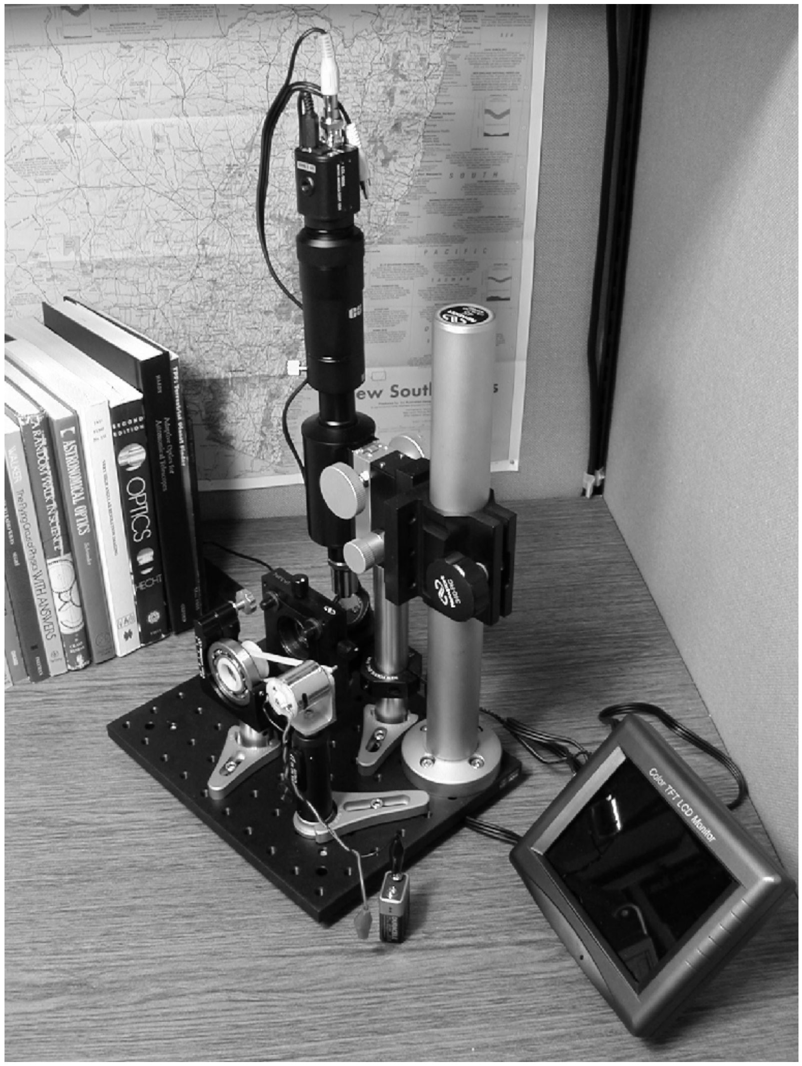

Figure 1. Overview of the desktop interferometer.

To illustrate the response of an interferometer, it is useful to have an artificial star that is a binary source and be able to rotate the source with respect to the two apertures of the interferometer. If the angular separation of the two components of the binary is made to be half a fringe spacing, then as the binary is rotated, the contrast of the fringes will change dramatically. It can then be left as an exercise for the students to determine the orientation of the binary in its orbit. The correct answer is immediately obvious when the two small holes are replaced by a single large aperture, whereupon the binary is fully resolved.

Image synthesis involves measurements with an interferometer using many different baselines, preserving the phase relationship between measurements. If a multi-aperture mask is used, in a similar manner as above, it is possible to observe several sets of fringe patterns simultaneously. By rotating the mask rapidly, fringes at all orientations of the mask become available. When displayed on a video monitor, these rapidly rotating fringe patterns will be seen to wash out in areas where the source is faint, and give rise to bright features where point sources exist. The relatively slow response of the eye allows all the fringe patterns to be integrated together and produce an image. For a simple source such as a binary, an image is easily synthesized.

3. APPARATUS

The interferometer in this demonstration, shown in Fig. 1, contains a telescope with an aperture mask mounted so that it can rotate rapidly in a bearing. A small monochrome CCD camera is used to display video images of fringes, and other video cameras are used to provide close-up views of the mask and the binary source.

The telescope is folded vertically so that it rests on as compact a base as possible. The base is a 8″×10″ breadboard, 0.5-inch thick, that rests on 0.5-inch legs. An optical beam height of 3 inches above the breadboard was chosen so that standard commercially available optical mounts could be used in the design.

3.1. Aperture Mask

A simple mask with four holes, shown in Fig. 2, was chosen with hole diameters, D, of 0.8 mm (1/32 inch). The hole locations in the mask are as follows, where the coordinates (x, y) are in units of inches measured with respect to the center of the array: hole 1 (-0.094, -0.047); hole 2 (0.000, -0.047); hole 3 (-0.094, 0.047); and hole 4 (0.094, 0.047). The 0.8 mm diameter of the holes was chosen so that their angular resolution would not resolve the components of the artificial binary star during the demonstration. This diameter also allows sufficient light through even from a white-light source, such as the filament of a MagLite, and is large enough to be drilled easily. With an HeNe laser and D=0.8 mm, $1.2\lambda/D$ corresponds to a separation of 1.7 mm at a distance of 6 ft. The artificial binary star was made with hole separations of 0.450 mm, which remain unresolved at this distance.

The aperture mask was mounted in a bearing so that it could be rotated by a DC motor. The bearing and mask are shown in Fig. 2, and the mounting is illustrated in the close-up views of the interferometer shown in Fig. 3. A bearing with an outer diameter of 2 inches was chosen to match the diameter of standard optical components, and a flange and mask diameter was then chosen to suit the bearing: the mask was mounted in a nylon flange which in turn was press-fit into the bearing.

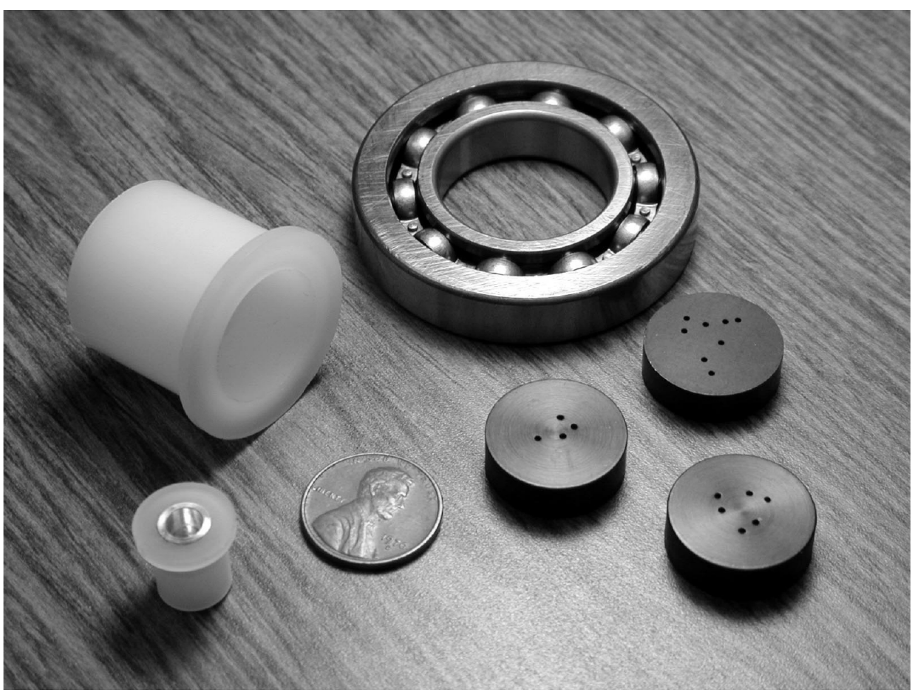

Figure 2. Parts and masks for the desktop interferometer. The bearing and large nylon flange used here are items 60355K19 and 6389K556 from the McMaster-Carr catalog, http://www.mcmaster.com/. The hole diameters D are 0.8 mm. The minimum hole spacing in the masks is $3D$ center-to-center. A 4-hole rectangular and 6-hole hexagonal mask are shown (Golay 1971) along with a mask to simulate the Keck Interferometer.

Figure 3. Views of the mask and DC motor. An elastic band runs between the motor and the nylon flange holding the mask. The motor used here is a 9–18 volt DC motor from Radio Shack, model 273-256.

3.2. Telescope/Microscope

The telescope is built from a microscope and an achromatic doublet. The magnification of the telescope is chosen to enlarge the diffraction spot from a hole in the mask, so that the Airy disk almost fills the field-of-view of the CCD camera. A 60× microscope objective and a f=50 mm, 25-mm diameter, achromatic doublet provide the necessary magnification. A replacement-type relay lens (from www.edmundoptics.com, model 37-820) is used to mount the 1/3" CCD camera on the microscope.

3.3. Artificial Binary Star

The artificial star, shown in Fig. 4, was built on the same principle as the aperture mask, but mounted on an adjustable base (Newport, model 37), which greatly facilitates the alignment. A small aluminium mask was machined with an outer diameter so that it would press-fit into a nylon flange, which then was pressed into a small bearing. Two small holes, 150 μm in diameter (#97 drill bit, the smallest drill available), were drilled in the aluminium mask, equally spaced about the center of rotation of the mask, with a center-to-center spacing (between holes) of three hole diameters, or 450 μm. The mask is illuminated by a diode laser through a filter wheel carrying an assortment of neutral density filters. The diode laser was chosen to provide a circular beam and be operated with a standard 9-volt battery.

4. PROCEDURE

4.1. Alignment

The alignment takes about 10 minutes. With a small audience it is best to perform the alignment from scratch in their presence, and hand out the parts for them to look at while the alignment is in progress. The simplicity of the alignment and the small number of simple components, adds greatly to the overall effect. The steps to the alignment are as follows:

Roughly align the source (Fig. 4) and the interferometer (Fig. 1), placing the two about 6 ft apart. Use a small amount of double-sided tape on the base of each to fix them in place. Check that the pupil of the beam from the source is centered at the height of the mask and unvignetted after reflection by the fold mirror. Adjust as necessary, then remove the mask and all optics, as well as the CCD camera, and put a paper target on the tube where the CCD threads into its mount. Adjust the vertical fold mirror to center the pupil of the beam at the camera. Install the optics, including lens, microscope objective, and CCD camera, but leave out the mask for now. Adjust the x-y position of the lens so that the focused laser beam is centered on the microscope

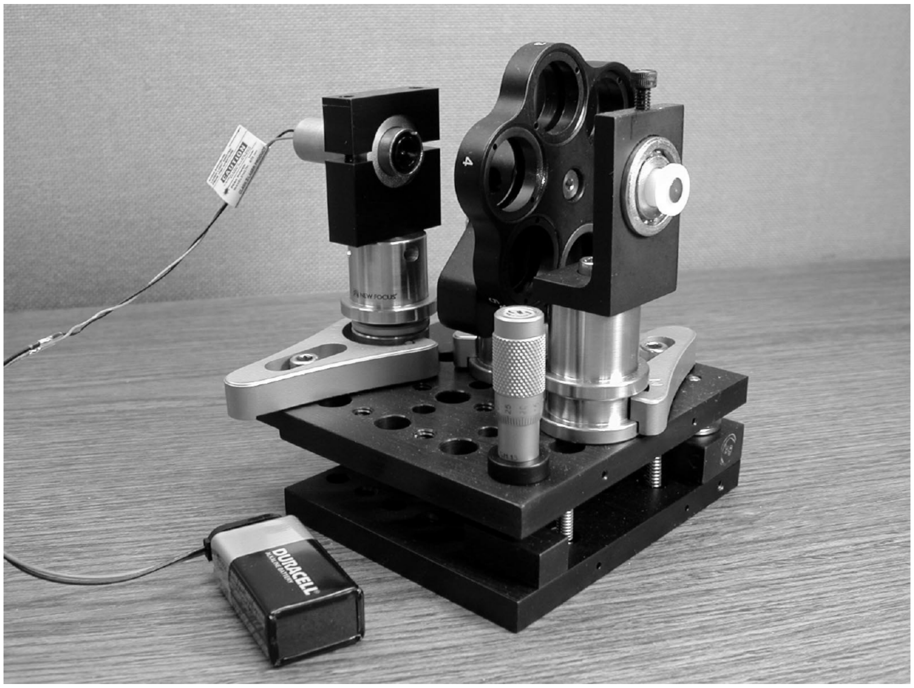

Figure 4. Artificial binary star.

objective. Turn on the CCD camera and view its output on a television monitor. Defocus the microscope and adjust the x-y position of the lens until you acquire the (saturated) beam on the monitor. Focus the microscope and re-adjust the x-y position of the lens as necessary to center it. You may need an neutral density of 3 or 4 to see the Airy rings and a clean focus without saturating the CCD. You should then clearly see the resolved binary. Center the mask in the pupil of the beam; on the video monitor you will then see a complicated fringe pattern that crosses the Airy disk and its first sidelobe. With close inspection you may notice that the Airy disk is not entirely symmetric but is slightly elongated in the direction of the binary. The binary is however unresolved.

4.2. Operation

Block all but one of the holes in the mask using common pins. Adjust the neutral density filters as necessary so that the Airy disk is clearly visible. What is shown is the diffraction pattern of a single hole, and it should be obvious to the students that the resolution in the measurements will be proportional to the width of the Airy disk.

1. Unblock a hole for one of the longer baselines. It should be evident that the fringe pattern that appears across the Airy disk now provides sensitivity to angular scales that are much smaller than the Airy disk itself. Rotate the mask and describe the fluctuations in visibility and how that relates to the geometry of the binary source.

2. Include several other baselines by unblocking all the holes. It is obvious that a lot more information is now available, but it should still appear mostly meaningless to the audience. Rotate the mask and show them that the fringe visibility on most baselines changes in a complicated manner. This is illustrated by the fringe patterns recorded in Fig. 5.

3. Attach the elastic band to the motor, and with a great flourish tell the students you are about to synthesize an image of the binary star. Turn the motor on and the binary should appear as in the long-exposure image of Fig. 6.

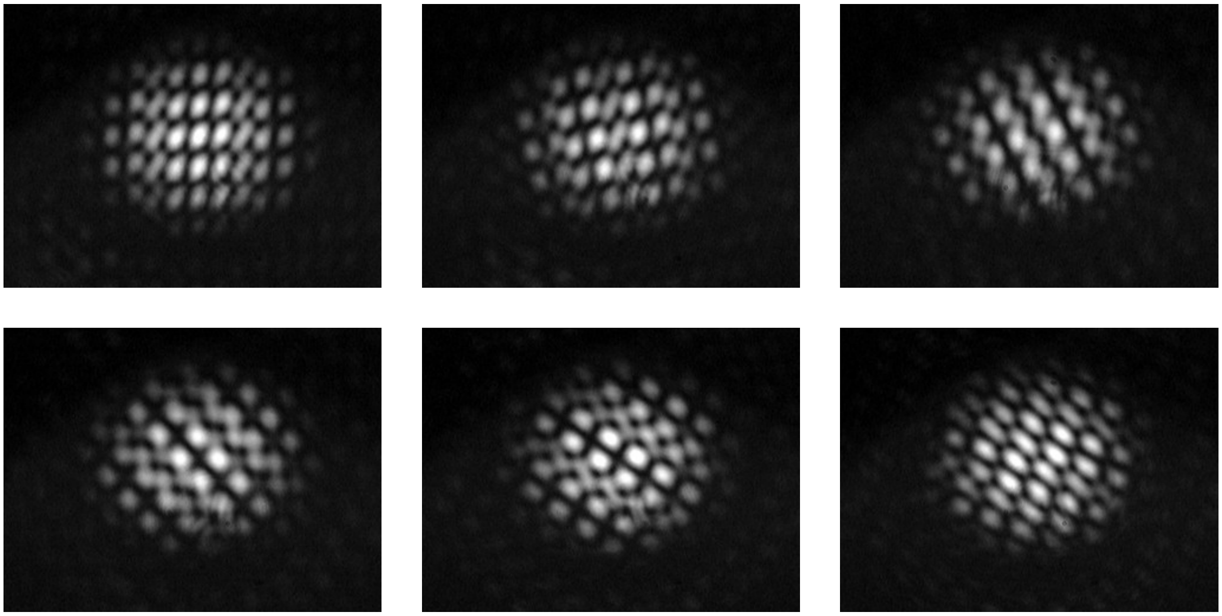

Figure 5. Actual fringes from a 4-hole mask observing a binary artificial star. Note the slow change in the fringe pattern as the mask is rotated.

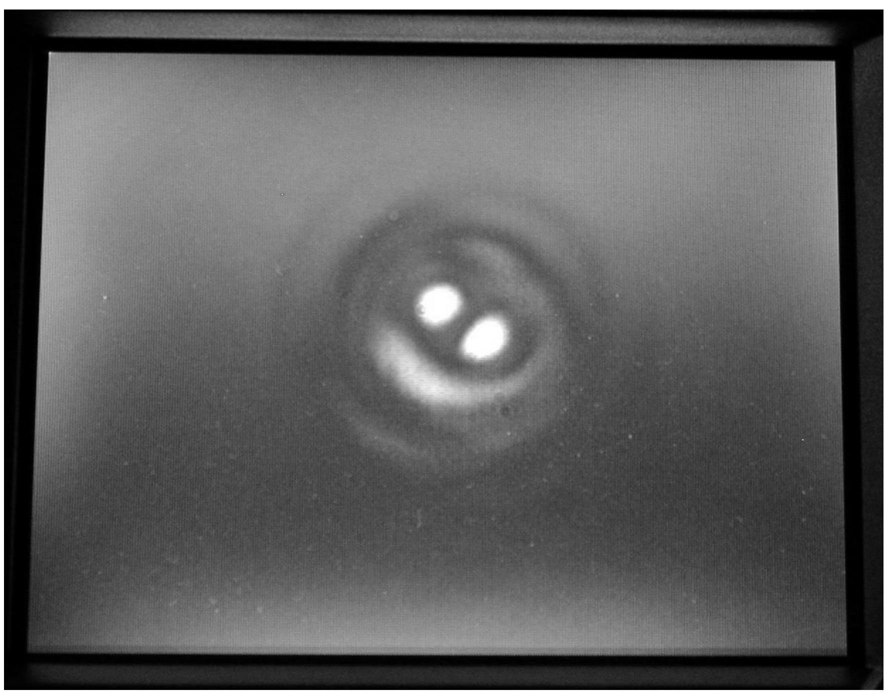

Figure 6. A synthesized image of the binary source, seen while the mask is being rapidly rotated by the motor. This is a long-exposure image of a video display.

5. RESULTS

Why does it work so well? Each point source gives rise to its own set of fringes. Each fringe pattern that crosses the Airy disk has a *central* fringe that runs through the angular position of the point source. When the fringes are rotated, they are blurred out everywhere except at the center of rotation, which remains at a constant intensity. The two point sources in the binary each provide a different center of rotation for their respective fringe patterns, and thus the sources appear distinct when the mask is rapidly rotated. The width of each unresolved source in the binary is then proportional to the fringe width.

A few caveats are in order. If the pupil of the beam in not properly centered on the mask, the intensity of the fringes will fluctuate and the synthesized images will not be as clear, or may degrade or improve when the binary source is rotated. Note also that it is important to use the appropriate neutral density filters so that the CCD camera does not saturate. If the camera saturates, then background features will become bright enough to distract the audience from the synthesized image of the binary.

6. CONCLUSION

The simplicity of the demonstration allows some fairly sophisticated concepts in synthesis imaging to be illustrated in a very straightforward manner. It is of course possible to make the demonstration much more elaborate, by using a video frame grabber and processing the data through software that would be more faithful to astronomical data reduction techniques. It would for example be possible to plot the fringes in the u-v plane, subtract the background, correct for biases in the power spectrum, and thereby produce a cleaner image. However, the simpler and more hands-on the demonstration can be made, the more effective it is and the more accessible it is to the students.

ACKNOWLEDGMENTS

The demonstration developed at the University of Cambridge[*] was partly inspired by a demonstration developed by Michael I. Large at the University of Sydney, which used rotating cylindrical lenses to illustrate the operation of the Molonglo Observatory Synthesis Telescope (MOST). The rapid rotation and relatively slow response of the eye are key to the success of these demonstrations. Work by PRL was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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[*]Photographs and information about the interferometer demonstration developed by Donald Wilson for COAST can be found at http://olbin.jpl.nasa.gov/news/coast/donald.html.